



Discharge and Sediment Transport Modeling before and after the Construction of a Dam at the Inlet of a Basin

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Abstract

The purpose of this study is the simulation of runoff and sediment transport in the basin of the Nestos River, Northern Greece, downstream of the Platanovrisi dam, whose construction was completed in 1997. The basin is predominantly forested and its area is 884 km². The model used for the simulation was AnnAGNPS, which is based on the Revised Universal Soil Loss Equation (RUSLE), combined with a GIS interface. AnnAGNPS requires daily rainfall and climatic data and should be calibrated and validated before its use. The purpose of calibration was to obtain values of *K* factor, for which the difference between simulated and measured values of discharge and sediment yield for year 1980 was minimum. The model was validated comparing simulated and measured values of discharge and sediment yield for year 1981, using the *K* factor values obtained from the calibration. Two different simulations were conducted, one for the years 1980–1990 and another for the period 2006–2030, before and after the construction of the dam, respectively. For the simulation for the period 1980–1990, existing meteorological data available on a daily basis were employed, and the results were in good agreement with those of a different study. The simulation for the period 2006–2030 was based on rainfall and climatic data generated from the software packages GLIMCLIM and ClimGen. The mean discharge was by 5% lower and the mean annual sediment yield by 20% lower than the corresponding values for the period 1980–1990.

Keywords AnnAGNPS · RUSLE · GLIMCLIM · ClimGen · Dam impact

Highlights

- AnnAGNPS was applied to evaluate sediment yield in a river basin downstream of a dam.
- Daily rainfall and climatic data were generated from GLIMCLIM and ClimGen models.
- Reduced values of discharge and sediment yield were obtained for the period 2006–2030.

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1 Introduction

Soil erosion is of great importance for a watershed, since it may have crucial effect on land loss and degradation. The soil erosion products are finally discharged into the main stream of the watershed, and, together with material eroded from the main-stream bed, compose the total sediment load of the stream. Sediment yield is defined as the total sediment outflow from a watershed during a specified time period, thus annual sediment yield corresponds to one year period. If the sediment yield is divided by the watershed area, the “sediment yield ratio” or “area-specific sediment yield” is obtained. The estimation of sediment yield at various temporal and spatial scales is of great importance for the design of major hydraulic projects, such as hydroelectric dams, reservoirs and flood attenuation structures.

The prediction of sediment yield of a watershed has been an ambitious goal for a variety of scientists, such as engineers, hydrologists and geologists at various parts of the globe. Many of these attempts aim to develop prediction formulae from field observations and measurements. Some measurements involve only suspended sediment load, which is proportionally much larger than bed load. A very comprehensive study is by Poulos et al. (1996), who studied mountainous rivers in Greece and proposed power relations of annual sediment load with the area of the basin, examining also the impact of flood events on seasonal variability of sediment fluxes. They quote extensive data from Alpine basins in southeastern Europe and make comparisons with the largest rivers of the world. Koutsoyiannis and Tarla (1987) examined the effect of hydrological and climatic parameters on sediment yield in rivers in western Greece and proposed an empirical relationship for the assessment of sediment load. Several attempts have been made to propose a predictive model of area-specific sediment yield (SSY) that will hold true in particular areas of the Mediterranean basin. Verstraeten et al. (2003) developed a scoring model for the prediction of SSY studying 22 reservoir basins in Spain. The model employed five factors, namely slopes, gullies, land cover, lithology, and shape of the basin. Those five factors were assessed in situ, their scores were multiplied and then added to a term depending on the area of the basin plus a constant. More recently, Karalis et al. (2018) examined the sediment yield in mountainous Greek watersheds using various sets of data, including those used in the studies by Poulos et al. (1996) and by Koutsoyiannis and Tarla (1987). They found that the principal controlling factors are slope and lithology, followed by precipitation, runoff and landslide frequency, and developed a model that employs slope, mean annual precipitation and lithology. It is interesting to note that, unlike the scoring model by Verstraeten et al. (2003), the study by Karalis et al. (2018) takes into consideration the influence of precipitation.

Computer modeling is considered to be a cost-effective tool for assessing the sediment yield of a watershed, especially when there is scarcity or complete lack of data from in situ measurements. An excellent review of erosion and sediment transport models is given by Merritt et al. (2003). In order to simulate the main processes of sediment transport, three categories of models (empirical, conceptual and physically-based) have been developed (Merritt et al. 2003; Kaffas and Hrisanthou 2015). Some common empirical models are the Universal Soil Loss Equation (USLE) (Wischmeier and Smith 1965, 1978), the Musgrave Equation (Musgrave 1947), the Dendy-Boltan Method (Dendy and Boltan 1976) and the Sediment Delivery Ratio (Renfro 1975). Empirical models are created for certain conditions, from field measurements and observations. The most widely used empirical model is the Universal Soil Loss Equation (USLE). A revision of USLE is the Revised Universal Soil Loss Equation (RUSLE) (Renard et al. 1997).

Conceptual models, such as the Sediment Routing Model (Williams and Hann Jr 1978), the Discrete Dynamic Model (Sharma and Dickinson 1979) and the Agricultural Catchment Research Unit (Schulze 1995) are based on the representation of a basin as a series of internal storages.

Physically-based models describe the natural procedure of streamflow and sediment transport in a basin. Some examples of physically-based models are the: Areal Non-Point Source Watershed Environment Response Simulation (Beasley et al. 1980), Chemical Runoff and Erosion from Agricultural Management Systems (Knisel 1980), Water Erosion Prediction Project (Lafren et al. 1991), and European Soil Erosion Model (Morgan et al. 1998). A comparative study of various models used to predict soil erosion and sediment yield has been conducted by de Vente et al. (2013). Hrissanthou (2002) used two mathematical models to estimate the annual sediment yield at the outlet of the Nestos River basin in Northern Greece. Both models consist of three submodels: a simplified rainfall-runoff submodel, a physically-based surface erosion submodel and a sediment transport submodel for streams. The two models differ only in the surface erosion submodel. The agreement between the annual values of sediment yield obtained from both models is satisfactory.

The USLE and RUSLE empirical models have been extensively used in various parts of the globe; their use has been facilitated by the development of Geographic Information Systems (GIS) software packages. De Roo (1998) used GIS techniques for the prediction of soil erosion employing the USLE model in the Catsop basin, The Netherlands. Cox and Madramootoo (1998) used the GIS technology for the application of RUSLE model in St. Lucia Island, which lies in the Eastern Caribbean. Kuok et al. (2013) employed the USLE Model for the estimation of sediment yield in Santubong River, Malaysia, emphasizing on the evaluation of C and P factors of the model. Liu et al. (2015) used RUSLE with a GIS tool, in order to predict the annual sediment transport rate in Jialing River Basin, China. Zarris et al. (2011) estimated the sediment delivery of Nestos River at the Thisavros reservoir site. This has been carried out by implementing USLE in a GIS environment for determining the mean annual soil erosion, in conjunction with suspended sediment measurements adjacent to the dam site. A sediment discharge rating curve between sediment and river discharges in a power form has been constructed using five alternative techniques. The mean annual sediment yield was found to be almost equal for all rating curve formulations. More recently, Efthimiou (2016) assessed the performance of RUSLE at three mountainous catchments of NW Greece. The performance was validated against sediment yield values, estimated from the sediment discharge rating curves methodology. The overall conclusion is that the behavior of the model is satisfactory, although the sediment yield was underestimated in some cases.

Several Non-Point Source (NPS) models have been developed to evaluate the sediment yield in a watershed (Bingner et al. 1992). Agricultural Non-Point Source Pollution Model (AGNPS) is a model developed for the study of pollution and sediment transport in agricultural or forested watersheds (Young et al. 1989). It was developed jointly by the Agricultural Research Service (ARS) and the Natural Resources Conservation Service (NRCS) of the United States Department of Agriculture (USDA). Since AGNPS is a single storm event model, the ANNUalized AGRicultural NonPoint Source model (AnnAGNPS) (Bingner and Theurer 2001a, 2001b) was developed, which is capable to simulate events continually, during one year or longer. Both AGNPS and AnnAGNPS have been used in various studies at different sites throughout the globe. Baginska et al. (2003), Polyakov et al. (2007) and Jordanidis and Anagnostopoulos (2012a) studied the pollution in various basins. Haregeweyn

and Yohannes (2003), Licciardello et al. (2007), Sarangi et al. (2007), Hua et al. (2012) and Ogwo et al. (2018) evaluated the sediment yield, whereas, Pease et al. (2010) estimated both sediment and pollution loads. To the authors' knowledge, these models have not been used previously for the evaluation of sediment yield in a basin within the Greek territory.

In this paper, the ANNualized Agricultural Non-Point Source Pollution Model (AnnAGNPS) was employed to predict runoff and sediment transport from a predominantly forested watershed of Nestos River, located in Northern Greece. In particular, the study area is the basin downstream of the hydroelectric dam of Platanovrisi, as depicted in Fig. 1. The construction of Platanovrisi dam, which is located approximately at the middle of the river's course inside the Greek territory, was completed in October 1997. The area of the basin under study is 884 km². Discharge and sediment yield were evaluated at the location Toxotes, at the outlet of the study area. Although AnnAGNPS was employed, it will be referred to as AGNPS in what follows, for reasons of brevity.

Extensive rainfall and climatic data, such as wind speed, relative humidity, temperature and solar radiation on a daily basis are necessary (Iordanidis 2010). Therefore, the lack of these data imposes a serious restriction on the application of the model. In case that data exist for a short year span, data for a longer interval can be generated, using rainfall and climatic models. Evidently, the generation of data is the only alternative for the use of the model for future predictions. In the present study two software packages, namely GLIMCLIM and ClimGen were employed, for the generation of rainfall and climatic data for the interval 2006–2030, from recorded data for the period 2006–2009.

The use of the model as a prediction tool requires its calibration and validation for the conditions prevailing in the study area. In the calibration process, the values of one or more selected parameters are adjusted, in a way that the measured values of discharge and sediment yield for a specific year approximate closely the values estimated by the model. In the present study, the erodibility (K) factor was selected as the key factor for the adjustment. The validity of the adjustment is confirmed, from the agreement between predicted and measured values of discharge and sediment yield in a different year, using the adjusted K factor values.

Two different simulations were conducted: one for the years 1980–1990, before the dam construction which was completed in 1997, and another for the period 2006–2030. The simulation for the years 1980–1990 was conducted using recorded data from two meteorological stations in the basin, whereas the simulation for the period 2006–2030 was based on rainfall and climatic data generated by the software packages GLIMCLIM and ClimGen. The results for the period 1980–1990 agree closely with those of a relevant study by Hrissanthou (2002), whereas the results for the period 2006–2030 show the influence of runoff on sediment yield.

2 The Study Area

Nestos is a transboundary river (Ganouliis et al. 2008), whose springs are located in Bulgaria; it flows through Bulgaria and Greece, and discharges into the North Aegean Sea (Fig. 1), where a Delta is formed. The Delta floodplain at the river outlet occupies an area of 450 km², and is of great ecological significance. The total river length is equal to 243 km, 130 of which lie within the Greek territory. The total watershed area occupies 5613 km², 2770 km² of which belong to Bulgaria and the rest 2843 km² to Greece. In the part of the river within the Greek

(a)



(b)

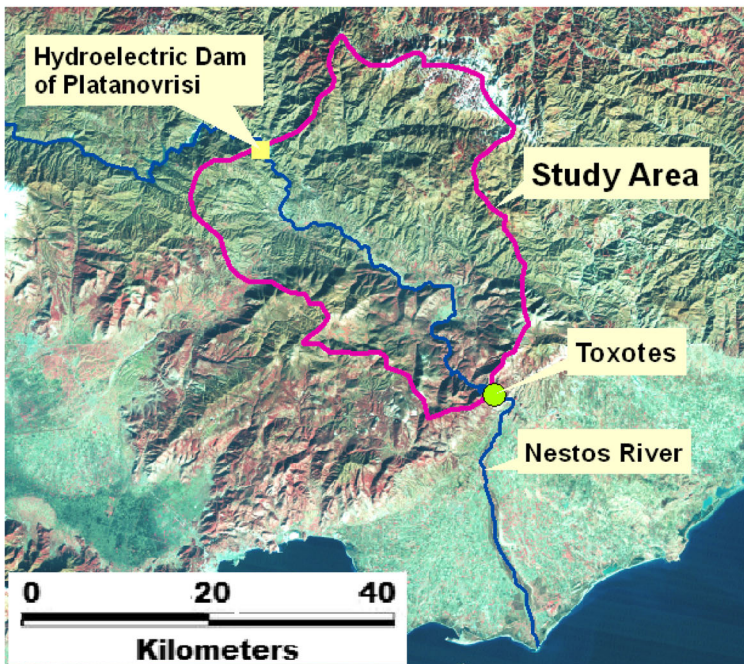


Fig. 1 a) The transboundary Nestos River basin (Ganoulis et al. 2008); b) the study area

territory, two hydroelectric dams have been constructed, namely the Thisavros dam upstream and the Platanovrisi dam downstream. The construction of Thisavros dam was completed in September 1996 and the construction of Platanovrisi dam in October 1997. A magnified map of the whole Nestos River basin, on which the two dams are clearly located, is provided by Zarris et al. (2011). Detailed information about the climatic conditions, geomorphology, land

uses, economic activities and other features of the area are provided by Zarris et al. (2011) and Paschalidis (2015).

3 Materials and Methods

Soil detachment, deposition and transport are important factors when modeling sediment loads in watersheds. Detached soil particles, apart from their potential effect in filling of lakes and reservoirs, may transfer harmful contaminants in downstream watercourses. AGNPS is a sediment and pollutant load modeling module, designed for risk and cost-benefit analyses. It is a batch process, continuous simulation, surface runoff computer model, which is suitable for studies of watersheds even of large scales. The model was developed for the simulation of long-term sediment and chemical transport from forest or agricultural watersheds. The basic modeling components are hydrology, sediment, nutrient and pesticide transport.

AGNPS is a daily time-step, distributed model, which enables the modeling of all different processes and parameters that affect sediment transport, allowing the creation of a detailed model of the study area (Bingner et al. 1992). It is based on the Revised Universal Soil Loss Equation (RUSLE) combined with a Geographic Information System (GIS) interface, for more convenient preparation of input data (Xiao 2003; Paschalidis 2015). RUSLE is a simple empirical model which is based on regression analyses of soil loss rates. It has the following structure, similarly to the USLE (Renard et al. 1997):

$$A = R \cdot K \cdot LS \cdot C \cdot P \quad (1)$$

where A is the spatial and temporal average soil loss [Mg/(ha year)]; R is the rainfall-runoff erosivity factor [MJ mm/(ha h year)]; K is the soil erodibility factor [Mg h/(MJ mm)]; LS is the slope length and steepness factor; C is the vegetation cover and management factor; and P is the conservation support practices factor. The LS , C , and P factors are dimensionless.

AGNPS is widely used because of its relative simplicity, robustness and ability to enable prediction of average annual soil loss by multiplying the factors of Eq. (1) together. AGNPS is characterized by Merritt et al. (2003) as conceptual model.

A large amount of input data is necessary for the model setup. AGNPS simulates runoff and sediment transport from land to streams, as a result of stormflow. Runoff is calculated in the model using a variation of the Technical Release 55 (TR-55) method (USDA-NRCS 1986). TR-55 employs simplified procedures to calculate runoff volume in small watersheds. A modified Einstein equation (Einstein 1950) was used for the sediment transport in the stream system of the watershed and the Bagnold equation (Bagnold 1966) was employed for the determination of the sediment transport capacity by particle size class. Bagnold (1966) used the concept of stream power to evaluate the rate of total load transport per unit channel width, as the sum of bed load and suspended load terms. Detailed description of the calculation procedure is provided in the Technical Documentation of AnnAGNPS (USDA-ARS and USDA-NRCS 2018).

In order to facilitate the processing of spatial data, AGNPS provides an ArcView GIS interface, in which the GIS tools for terrain processing can be utilized (De Roo 1998). The most important of these tools are the Digital Elevation Model (DEM) Manipulation tool used for the determination of the watershed boundary, the Digital Elevation Drainage Network

Model (DEDNM) tool used for both the river basin discretization and the hydrologic network delineation, and the land use and soil texture data spatial input (Iordanidis 2010). It should be mentioned that the current version of AGNPS provides a built-in GIS interface, based on the MapWinGIS software suite.

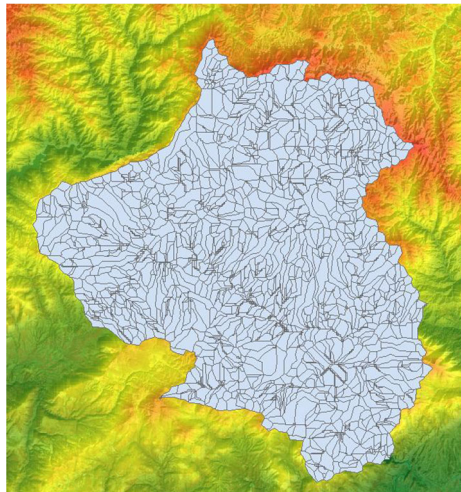
3.1 Watershed Discretization

For the determination of the watershed boundary a Digital Elevation Model (DEM) with cell resolution 100×100 m was employed. Initially the outlet of the basin (location Toxotes) was specified and then the Digital Elevation Model (DEM) Manipulation tool, which is a built-in module of AGNPS, was used for the delineation of the watershed boundary. In order to adjust the boundary of the basin at the location of the Platanovrisi Dam according to the requirements of AGNPS, the digital elevation model of the study area was modified locally, in a way that the gap was replaced by a virtual boundary, and the discharge of the dam was represented as a point source of water.

Using the Digital Elevation Drainage Network Model (DEDNM) tool of AGNPS, which is a module of TopAGNPS, the basin was discretized into cells and channel reaches. The discretization was based on the Critical Source Area (CSA) and Minimum Source Channel Length (MSCL) parameter values. Critical source area is the minimum area for which a cell can be generated, and minimum source channel length is the minimum possible length for the generation of a channel reach. AGNPS offers the capability to use up to five different value pairs for the CSA and MSCL parameters.

AGNPS uses amorphous cells, which result from the grouping of individual square grid elements. Since no significant variations within the basin were detected, the selected values for CSA and MSCL were 55 ha and 150 m, respectively, for the entire study area. MSCL should not be lower than the DEM cell resolution (100 m). In the present study a value for MSCL close to the lowest permitted was specified, in order to represent the drainage network accurately. Figure 2 depicts the final discretization of the study area into 1568 cells. The Digital Elevation Model in the background, outside the basin, is also shown. Although the area of the great majority of cells is slightly above 55 ha, which is the

Fig. 2 Area discretisation into 1568 amorphous cells. The Digital Elevation Model (DEM) can be seen in the background, outside the basin



value of CSA, there exist few cells whose area is approximately 250 ha. The cell attributes include the drainage area, average elevation, average slope, shallow flow slope and length, concentrated flow slope and length, and the *LS* factor, which computes the effect of slope length and steepness on erosion.

Introducing an upper limit for the number of cells discharging into the cell under consideration, the drainage network was determined for MSCL equal to 150 m. The drainage network, which comprises 699 channel reaches, is illustrated in Fig. 3. The reach attributes include drainage area, contributing cells, receiving reaches, average elevation and channel slope and length.

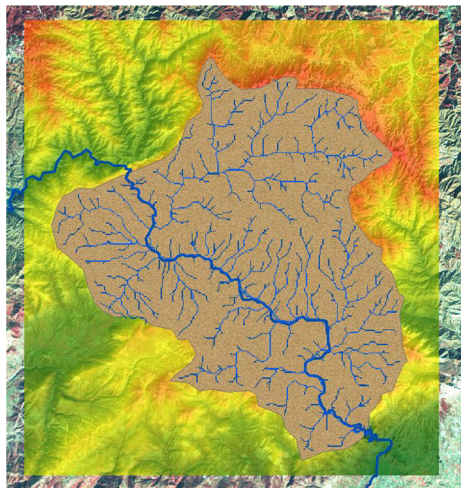
3.2 Land Use Data

Land use data were acquired from the European Environmental Agency in raster form. There exist sixteen distinct land uses in the study area, as illustrated in Fig. 4. ArcView version 9.3 was used for the conversion of raster data into shapefile format, and the AGNPS/ArcView interface was employed afterwards for the determination of the land use in each cell of Fig. 2. According to the existing land use data, the cells within the watershed were classified into groups for more convenient handling and management.

Land uses in AGNPS are classified into two major categories: (a) Non-cropland; (b) Cropland. From the sixteen land uses in the study area, 13 are “non-cropland uses” and include urban infrastructure, wooded land and other non-cultivated land uses. Annual Rainfall Depth, Annual Cover Ratio, Root Mass and Surface Residue Cover were inputted in order to simulate non-cropland uses.

The main crops cultivated in the area are grains (not irrigated). Cropland land uses contain crop-related activities such as sowing and harvesting. Since the study area contains cropland land uses, it is necessary to simulate the effects of agricultural activities, including their time schedule during a year. The connection of each land use with the above activities was assigned via the input editor and specifically the “Field Data Management” option. Each field data contains one or more events (such as sowing and harvesting), which are scheduled to take place at a specific time of the year. The time period for each event was determined through the

Fig. 3 The drainage network of the study area, consisting of 699 channel reaches



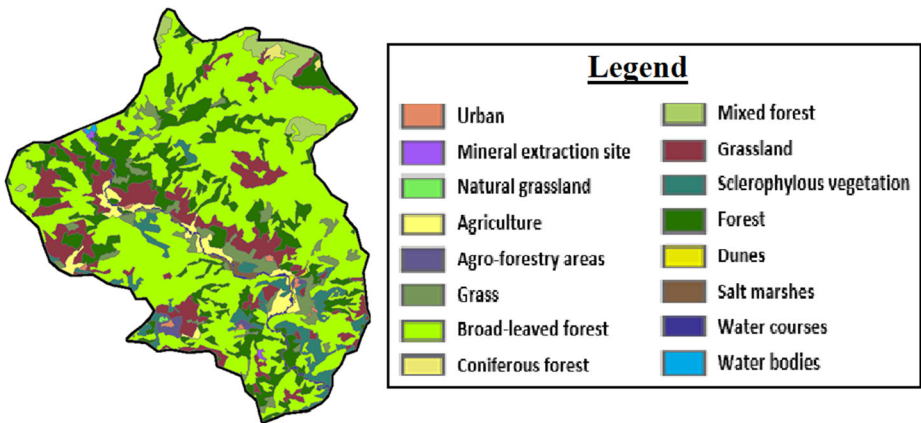


Fig. 4 The land uses of the study area

“Management Schedule” option. Detailed information regarding cropland land uses became available from regional authorities. Irrigated lands do not exist in the study area, thus the relevant option provided by AGNPS was not needed.

3.3 Soil Parameterization

Four main soil types exist in the study area, according to maps from the Institute of Geology and Mineral Exploration (IGME), whose distribution is illustrated in Fig. 5. The textures of the soil samples obtained from various locations in the basin were identified and categorized per soil type by the Hellenic Authority of Reclamation (YEB). For each soil type, the average texture was calculated and a specific code number was assigned to each soil type. The average textures for the four soil types are quoted in Table 1. Sandy Clay Loam soils are dominated by sand particles, but contain enough clay to provide cohesion and fertility. Clay soils have greater strength, especially when they are dry and are susceptible to waterlogging, due to poor infiltration and aeration (Melonas 2004).

Fig. 5 Soil map of the study area

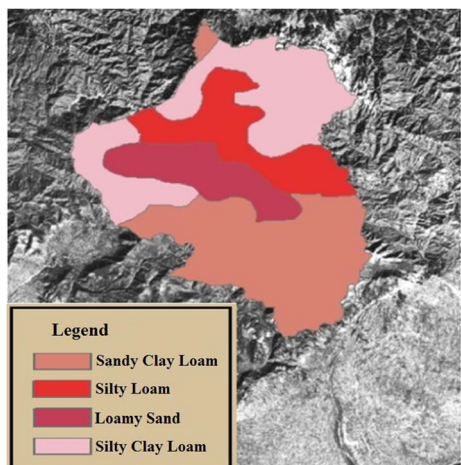


Table 1 Average texture of the various soil types

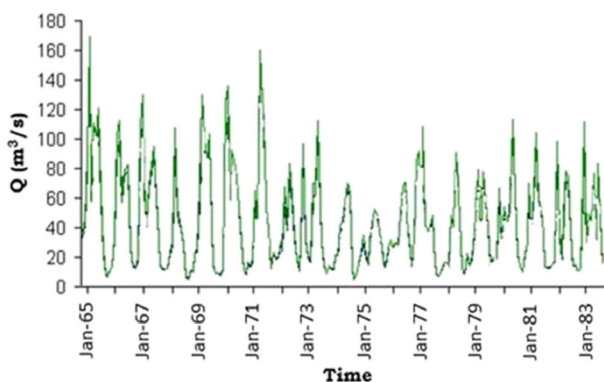
Soil Type	Sand (%)	Clay (%)	Silt (%)
Sandy Clay Loam	55	19	26
Silty Loam	22	21	57
Loamy Sand	78	4	18
Silty Clay Loam	8	39	53

Twelve soil hydraulic parameters, such as bulk density of soil, saturated hydraulic conductivity, field capacity and wilting point, out of a total of 28 parameters included in AGNPS, were used to simulate the runoff and sediment transport in the watershed. The values of these parameters for each soil type were derived using the module “Soil Water Characteristics” of the Soil Plant Atmosphere Water (SPAW) hydrology model, which has been developed by the USDA (Madramootoo and Norville 1990). The soil parameters mentioned before were assigned to each of the four soil types via the input editor. The AGNPS/ArcView interface was then used to assign the soil type to each cell of Fig. 2, through an automated procedure. Consequently, the values of the parameters corresponding to each cell were also assigned.

3.4 Discharge and Sediment Data

Discharge and sediment measurements in the study site have been conducted by the Hellenic Public Power Corporation (HPPC), from which the relevant data were obtained. Although special attention was given at the locations where the construction of dams was planned, measurements were also conducted at various stations along the river, up to the basin outlet at Toxotes.

For the location of Platanovrisi dam mean monthly discharges have been published for the period 1964–1997. Data of mean daily discharges exist only for the period 1980–1997, therefore, there is lack of data regarding mean daily discharges for the period 1964–1979. The mean monthly flow rates at the location of Platanovrisi dam for the period October 1964 to October 1983 are depicted in Fig. 6, and their average values for the same period in Fig. 7. The Hellenic Public Power Corporation has conducted 114 instantaneous sediment measurements with simultaneous measurements of river discharge for the years 1964 - 1983. As

**Fig. 6** Mean monthly flow rate at Platanovrisi dam for the period October 1964 to October 1983

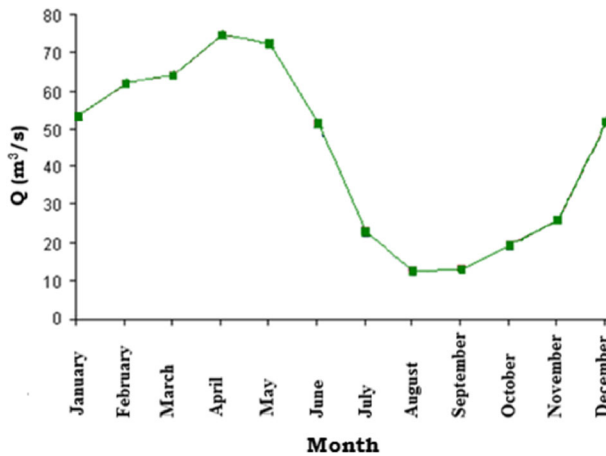


Fig. 7 Average mean monthly flow rate at Platanovrisi dam for the period 1964–1983

quoted by Zarris et al. (2011), the suspended sediment discharge sampling is infrequent, since there are long periods with no measurements at all, and the majority of the measurements refer only to low or medium flows.

Discharge measurements at various stations along Nestos River, including location Toxotes (Fig. 1), have been conducted by HPPC for the interval 1964–1997. Mean monthly discharges for the period 1980–1997 have become available also by the Hellenic Ministry of Agriculture. Measurements of sediment yield were conducted by HPPC for the period 1964–1983. Similarly to the dam locations, the measurements were infrequent with long periods without measurements, thus only for a few years, including 1980 and 1981, the annual sediment yield of the basin could be determined.

3.5 Meteorological Data

Meteorological (rainfall and climatic) data were obtained from two meteorological stations inside the basin (Fig. 8). The locations of stations 1 and 2 were Prasinada and Mesochori, respectively. AGNPS requires detailed meteorological data on a daily basis for the simulation period, stored in a separate file. The meteorological data of the two stations contain eight daily parameters: date, precipitation, daily maximum temperature, daily minimum temperature, dew point temperature, sky cover or solar radiation, wind speed and wind direction. This is the minimum information required to calculate surface runoff and other physical processes, which are simulated by AGNPS.

The two meteorological stations mentioned previously contain monthly rainfall and climatic data for the period 1964–2009. Complete sets of data on a daily basis suitable for use by AGNPS exist only for the periods 1980–1990 and 2006–2009. Stochastic time series of the necessary meteorological parameters at a daily time step for the period 2006–2030 were generated with the use of two software packages, namely GLIMCLIM and ClimGen. The data for the period 2006–2009 were used for the calibration of these two software packages. After their calibration, GLIMCLIM was used to estimate daily rainfall values in the study area for the period 2006–2030 and ClimGen was used to estimate the daily values for all the other meteorological parameters for the same period.

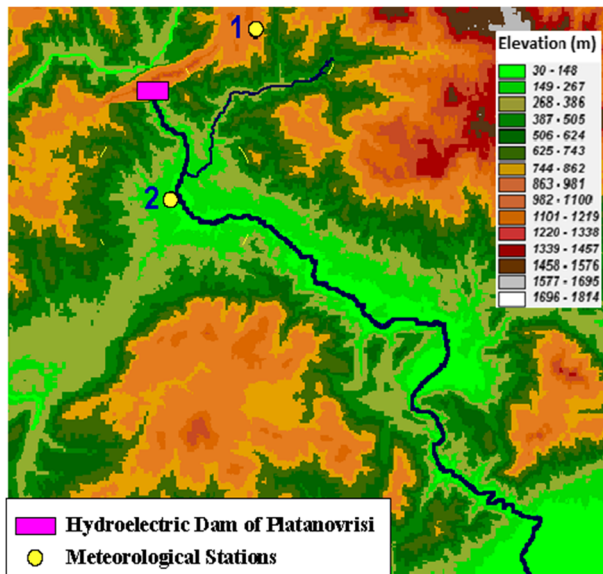


Fig. 8 The terrain of the study area with the two meteorological stations. Station 1 is located at Prasinada and station 2 at Mesochori

GLIMCLIM is a statistical rainfall estimation tool which incorporates the theory of Generalized Linear Models (GLMs) and allows for the quick and reliable generation of stochastic rainfall time series. The software has been developed by Chandler (2002), in collaboration with the Department of Civil Engineering of the Imperial College of London. It can be used to generate time series of data for areas up to $100 \times 100 \text{ km}^2$ (Yang et al. 2005). It has been applied already to the basin of Drama, which is adjacent to the area of the present study (Iordanidis and Anagnostopoulos 2012b). That study has confirmed that the model is capable of generating reliable data series in regions with Mediterranean climate conditions. The GLIMCLIM package consists of three modules, namely the Logistic-Events, the Gamma-Magnitude and the simulation module. The Logistic-Events module is used to generate the rainfall events for the study period, determining whether rainfall will occur or not, on a given day. The Gamma-Magnitude module calculates the amount of rainfall in a day for which the Logistic-Events module has determined that rainfall will occur. The parameters of the Logistic and the Gamma module are calibrated using input data from stations within the study area. Finally, the simulation module is employed for the estimation of daily rainfall values for the period examined, using the parameters that were calibrated from the two other modules.

A necessary stage before using the data generated by GLIMCLIM is the statistical test of the reliability of the time series. The verification is implemented by calculating the values of selected statistical measures (such as the maximum and minimum values of monthly rainfall) from the generated data and comparing them with the corresponding values calculated from the recorded data (Iordanidis and Anagnostopoulos 2012b). The set of data for the period 1980–1990, available on a daily basis, was used for the generation of a large number of daily time series of rainfall for the period 1964–2009, for which monthly data exist. For each of these time series, the total monthly rainfall was calculated throughout the period examined. Then, for each simulation, the maximum monthly rainfall value was selected for each of the twelve months, regardless of the year of occurrence. The same procedure was followed for all

simulations. Thus, a $n \times 12$ table was created, where n is the total number of simulations. Each element of the table refers to the maximum monthly rainfall for each simulation. The last step was to determine the maximum value for each column, which yields the maximum monthly rainfall for the entire time span of the simulation.

The maximum monthly rainfall height estimated from GLIMCLIM at Stations 1 and 2 of Fig. 8 for the period 1964–2009 are illustrated in Fig. 9. The maximum recorded monthly rainfall height for the period 1964–2008 is also displayed in these diagrams. The simulation values are slightly higher than the recorded data, except from August to October for Station 1 and for August for Station 2. Therefore, the simulation can be considered reliable (Yang et al. 2005).

The simulation module of GLIMCLIM was then used to estimate daily rainfall values in the study area for the period 2006–2030. A large number of simulations (approximately 1000) was conducted for this period. Since GLIMCLIM is a statistical model, the large number of simulations serves in obtaining an adequate sample of estimated values of rainfall for each

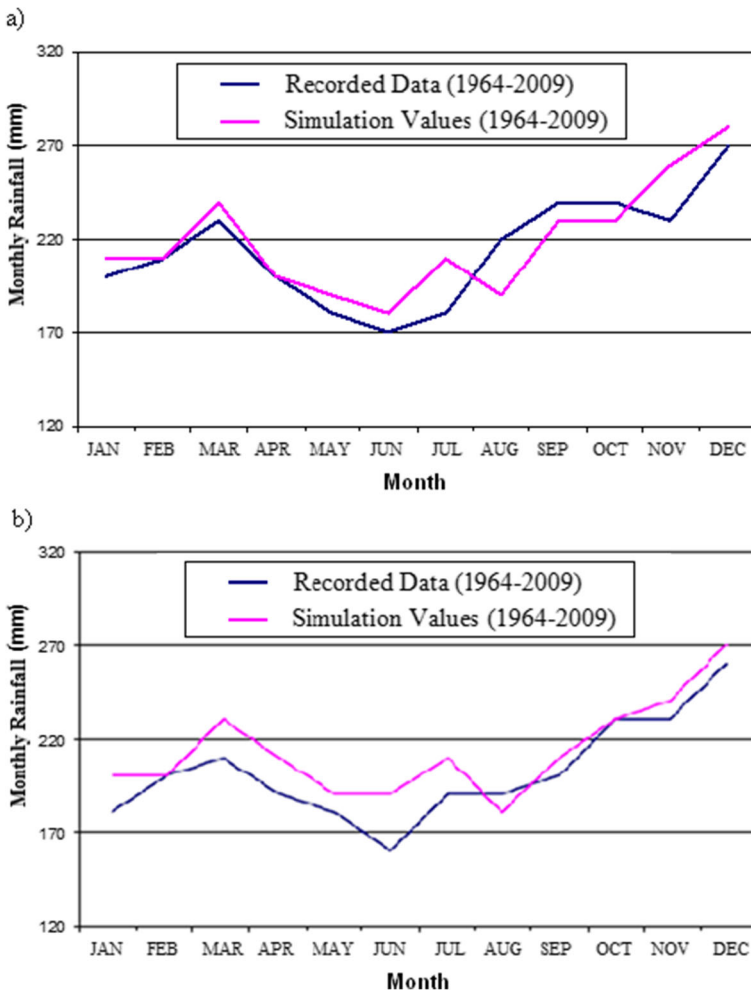


Fig. 9 Maximum monthly rainfall at the meteorological stations of Fig. 8. a) Station 1; b) Station 2

day in the simulation period. For all simulations, the rainfall for each day in the interval 2006–2009 was compared with the corresponding recorded value. The simulation which yielded daily estimated rainfall closest to the recorded throughout the interval 2006–2009 was selected as the most reliable.

ClimGen is a climate data generation software, which has been developed by Stöckle and Nelson of the Washington State University, in cooperation with the USDA (Stöckle et al. 2001). ClimGen uses Universal Environmental Database (UED) files which store daily data for the maximum and minimum temperature, the maximum and minimum relative humidity, dew point temperature, sky cover or solar radiation, wind speed and wind direction. ClimGen employs an algorithm that calibrates the climate generation parameters automatically from the input data. These parameters are then used to generate stochastic time series at a daily step for each of the weather parameters mentioned previously. Similarly to GLIMCLIM, a large number of simulations were conducted for the period 2006–2030. The simulation which yielded daily climate data closest to the recorded for the interval 2006–2009 was selected as the most reliable.

3.6 Model Implementation

In order to calculate runoff, AGNPS uses the Curve Number method. This method uses the following equations:

$$Q = \frac{(WI - 0.2S_{cn})^2}{WI + 0.8S_{cn}} \quad (2)$$

with

$$S_{cn} = 245 \left(\frac{100}{CN} - 1 \right) \quad (3)$$

where Q is the surface runoff per unit area for each cell, WI the water input (precipitation or irrigation), S_{cn} the retention variable and CN the Curve Number. The quantities Q , WI and S_{cn} are expressed in mm. The Curve Number depends on the land use and soil type of each cell, as described by TR-55. Hydrologic models are in general sensitive to the values of CN (Kaffas and Hrisanthou 2014), which range between 30 and 100. The Curve Number value decreases as the soil permeability is increased. Therefore, lower CN values are associated with low runoff potential, whereas larger values indicate increased runoff potential. Initially, the land use of the corresponding cell is identified, according to the classification of Fig. 4. Considering also the soil type of the cell, the appropriate CN value is selected from tables published in TR-55 (USDA-NRCS 1986) and the runoff of the cell is evaluated from Eqs. (2) and (3).

The annual sediment yield ratio, S_y , (Mg/ha) for each cell is calculated by

$$S_y = 0.22Q^{0.68} \cdot q_p^{0.95} \cdot K \cdot LS \cdot C \cdot P \quad (4)$$

where q_p the peak rate of surface runoff (mm/s) and K , LS , C and P are factors of the Revised Universal Soil Loss Equation (RUSLE) defined previously (Wischmeier and Smith 1965, 1978).

The most important of these factors is the soil erodibility factor, K , which influences the spatial variability of sediment losses. Factor K , which is important for the determination of the

sensitivity of soil to erosion, the sediment transportability and runoff rate, is directly related to soil properties. Soil texture, structure and particle composition are the main factors affecting soil erodibility. The values of K factor range typically from about 0.10 to 0.45 [Mg h/(MJ mm)]. Several formulae have been developed for the determination of K factor (Wang et al. 2016); the most widely used are USLE developed by Wischmeier and Smith (1978) and EPIC (Erosion Productivity Impact Calculator) developed by Sharpley and Williams (1990). The former is based on the particle size parameter, the organic matter content, the soil structure and the soil permeability, whereas the latter requires only the soil particle size distribution and the soil organic carbon content for the determination of K factor values. Cox and Madramootoo (1998) and Parsakhoo et al. (2014) employed the USLE formula, whereas Liu et al. (2015) favoured the EPIC formula. Similarly to Liu et al. (2015), the erodibility factor K in the present study was calculated using the EPIC technique given by Eq. (5):

$$K = 0.2 + 0.3 \exp \left[-0.0256 S_d \left(1 - \frac{S_i}{100} \right) \right] \left(\frac{S_i}{C_l + S_i} \right)^{0.3} \left[1.0 - \frac{0.25 C_o}{C_o + \exp(3.72 - 2.95 C_o)} \right] (5)$$

where S_d is sand content, S_i is silt content, C_l is clay content and C_o is soil organic carbon content.

The slope length and steepness factors, LS , indicate the impact of terrain topography on soil erosion. Slope length is defined as the distance from the point of origin of overland flow to the point where either the slope decreases sufficiently for deposition to occur, or runoff waters are streamed into a channel. The slope length factor, L , can be evaluated for each grid cell from the slope length, as explained by Wang et al. (2009) and Panagos et al. (2015). The steepness factor, S , depends on the change in elevation at a specified distance and can be evaluated from the slope gradient (Wang et al. 2009; Panagos et al. 2015). The terrain slopes in the study area are depicted in Fig. 10. In the present study L and S factors were evaluated by AGNPS, using the Digital Elevation Model. Although L and S factors are calculated separately, it is customary to appear as a combined term (Van Remortel et al. 2001).

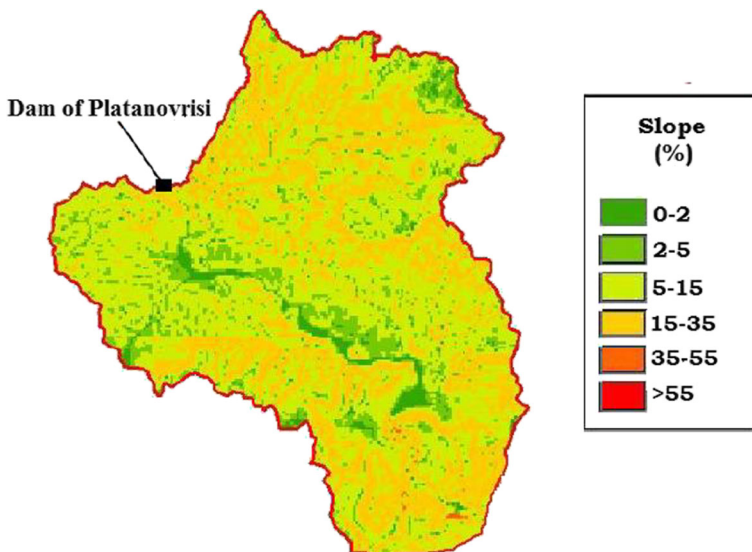


Fig. 10 Terrain slopes in the study area

The vegetation cover and management factor, C , represents the effect of both the natural vegetation cover on reducing soil loss in non-agricultural situations, and of cropping and management practices in agricultural activities. Liu et al. (2015) obtained C factor values in terms of the annual averaged vegetation cover, while Kuok et al. (2013) report values for various land use types such as forest, grassland and farmland. In the present study, the C factor was calculated by the model for all non-water cells in the study area, depending on the land use (cropland or not). For cropland cells, AGNPS calculates 24 values of C factor for each year, and an average C factor for each year for non-cropland cells. For cropland land uses, the effects of agricultural activities, such as sowing and harvesting, and their time schedule during a year, are important for the determination of C factor. The effects of agricultural activities and their time schedule during a year, are inputted for each cropland cell, as mentioned previously.

The conservation support practice factor, P , is the ratio of soil loss under a particular conservation support practice, such as contour-cropping, strip-cropping and terracing, to soil loss for cultivation along the slope direction, with no conservation support (Meyer 1984). Kuok et al. (2013) quote P factor values equal to 0.60 for contouring, 0.35 for strip-cropping and 0.15 for terracing. It is evident that lower P factor values are associated with better practices for controlling soil erosion. Similarly to C factor, P factor is calculated by the model for all non-water cells in the study area. The model uses RUSLE Predefined Cover Codes for each land use. AGNPS calculates sub-factors for contour cropping, strip-cropping and terracing, from which the P factor of the corresponding cell for each year is evaluated. For strip-cropping, the effect of different cropping practices, even at previous years, is taken into consideration.

4 Results and Discussion

4.1 Calibration and Validation

The calibration and validation of the model are necessary stages prior to its use for predictions. In case that the model prediction for discharge and sediment yield at the outlet of the basin over a specified interval agrees closely with measured values, the reliability of the model is confirmed, thus no further action is required. In case of discrepancy, the model should be calibrated by adjusting some of its parameters, in a way that the difference between predicted and measured values is minimized. Next, the model should be validated for a different period, in order to confirm the validity of these adjustments.

Year 1980 was selected for the initial check and the possible calibration of the model. Measured values of the daily discharge from Nestos River into the basin and daily meteorological data were available for this year, together with measurements of the discharge at the outlet of the basin (location Toxotes). Data of sediment yield at the inlet and outlet of the basin were also available, which allowed by subtraction for the estimate of the net sediment yield in the basin for this year.

As stated previously, the soil erodibility factor, K , is of primary importance for the evaluation of the annual sediment yield. The values of K for the four soil types of the present study, as calculated from EPIC Eq. (5) using the data of Table 1, are listed in Table 2. The soil organic carbon content, C_o , was taken equal to 2% for the entire area, since related measurements, including neighbouring regions, were very scarce. Apparently, this induces an uncertainty in the calculated K factor values. In any case, an increase of C_o value above 2% has very

Table 2 Calculated from EPIC formula and calibrated K factor values

Soil Type	K (calculated)	K (calibrated)
Sandy Clay Loam	0.197	0.314
Silty Loam	0.302	0.272
Loamy Sand	0.189	0.223
Silty Clay Loam	0.316	0.285

small, almost negligible, effect on K factor. The values in Table 2 are close to those reported by Liu et al. (2015), which lie in the range between 0.278 and 0.344. However, serious discrepancies have been reported between estimated and observed values of K factor in other studies (Shabani et al. 2014; Ostovari et al. 2016; Wang et al. 2016). Shabani et al. (2014) report that K is markedly influenced by the content of lime and slope, as well as land use and permeability. EPIC formula, which relies only on sand, silt, clay and soil organic carbon content, does not take into account these factors.

The results of the simulation obtained for K factor values calculated from EPIC formula are listed in Table 3. The values of annual sediment yield are expressed in tons per year, t/y, although the division “per year” may be considered as redundant according to the definition. This has been done mainly for reasons of compatibility with other studies. These results contain the simulated values of the mean annual discharge and the sediment yield for the year 1980 at the location Toxotes. The corresponding measured values are also listed. As mentioned previously, AGNPS works on a daily time step, therefore, daily values of discharge and sediment outflow are evaluated. From the computed daily values of discharge, the mean monthly discharge values are evaluated, which yield finally the mean annual simulated value. The discrepancy between measured and simulated mean monthly discharges for year 1980 was no greater than 9%. The annual sediment yield for year 1980 resulted from the addition of the daily sediment outflow values for this year. It can be seen that the values of both the discharge and the sediment yield obtained from the simulation are lower than the measured, by 7.05% and 17.85%, respectively.

The discrepancy between measured and simulated values of discharge, although noticeable, is not large. The discharge is associated with surface runoff, which depends strongly on CN values. This provides evidence that the selection of CN values was appropriate. The discrepancy for the sediment yield, although can be considered within acceptable limits (Liu et al. 2015) is rather large. The parameter most responsible for this discrepancy was considered to be the K factor, since, as previously stated, in spite of its importance, its calculated values are rather approximate. The values of LS and C factors are calculated rather accurately, whereas a possible uncertainty in determination of P factor has small effect, since the cultivated land is proportionally small. Preliminary tests were conducted, to investigate the impact of K factor of each of the four soil types of the study area on runoff and sediment yield. This was implemented by modifying the K factor value of one of the soil types, keeping the values of the other three soil types constant. It was found that the results, especially of sediment yield, were susceptible even to small changes of K factor values, especially for Sandy Clay Loam. Since the value of K factor for Sandy

Table 3 Mean discharge and sediment yield at the location Toxotes for year 1980. The K values used in the simulation were calculated from EPIC formula

	Measured values	Simulated values	Deviation
Discharge (m ³ /s)	48.66	45.23	7.05%
Sediment yield (t/y)	298,000	244,781	17.85%

Clay Loam obtained from EPIC formula yielded underestimated results, it was considered reasonable to test larger K values.

A very large number of tests was conducted, for the determination of the K factor values, which yielded values of mean annual runoff and sediment yield for the year 1980 as close as possible to the measured values. These values, denoted as “calibrated”, are listed in the right column of Table 2. With the exception of Sandy Clay Loam, whose calibrated K value was significantly higher than the calculated, the calibrated K values of the other three soil types were rather close to the evaluated from EPIC formula. The calibrated values of Silty Loam and Silty Clay Loam were by 10% lower than the calculated, whereas the calibrated value of Loamy Sand was by 15% higher than the calculated.

The results of mean annual discharge and sediment yield at the location Toxotes using the calibrated K values are listed in Table 4, together with the corresponding measured values. The simulated discharge value is now 5.24% lower than the measured and the simulated sediment yield 5.25% lower than the measured. It is interesting to note that the simulated values of discharge in Tables 3 and 4 are slightly different, although the K factor appears only in Eq. (4) which influences soil erosion and not in Eqs. (2) and (3), from which the surface runoff is evaluated. This happens because the erosion process induces slight modifications in the drainage network, which, in turn, influence, even by a small amount, the discharge.

A necessary step before using AGNPS as prediction tool in the study area was its validation. In case that the evaluated values of runoff and sediment yield at the location Toxotes in a year different from 1980 were close to the measured, the model is considered as validated. Year 1981 was selected for the validation, using the calibrated K factor values. The daily inflow into the basin and the available climatic and rainfall data for 1981 were used for the validation. As deduced from Fig. 6, the mean annual inflow from Nestos River was almost the same for years 1980 and 1981, very close to 46 m³/s, in spite of differences of the mean monthly flow rate. The results are listed in Table 5. It is evident that the simulated values of both discharge and sediment yield agree closely with the measured, which confirms the reliability of calibrated K factor values. It should be noted that a similar simulation for 1981 using the calculated values of K yielded discharge and sediment yield lower than the measured by 3% and 20%, respectively. The measured and simulated values of discharge and sediment yield for years 1980 and 1981 are summarized in the bar plots of Fig. 11.

Table 4 Mean discharge and sediment yield at the location Toxotes for year 1980, using calibrated K factor values

	Measured values	Simulated values	Deviation
Discharge (m ³ /s)	48.66	46.11	5.24%
Sediment yield (t/y)	298,000	282,364	5.25%

Table 5 Mean discharge and sediment yield at the location Toxotes for year 1981, using calibrated *K* factor values

	Measured values	Simulated values	Deviation
Discharge (m ³ /s)	54.10	53.21	1.65%
Sediment Yield (t/y)	497,000	515,476	3.72%

4.2 Simulations

Two different simulations were performed using AGNPS, one for the period 1980–1990 and the other for the period 2006–2030. The purpose of both simulations was the evaluation of the mean annual discharge and of the annual sediment yield at the outlet of the river Nestos basin (location Toxotes).

The period 1980–1990 was selected, because detailed meteorological data on a daily basis were available from the two meteorological stations within the basin. Although no measured values of sediment yield were available after 1983, estimated values were provided by Hrisanthou (2002) at the same location and period of time. Table 6 presents the calculated

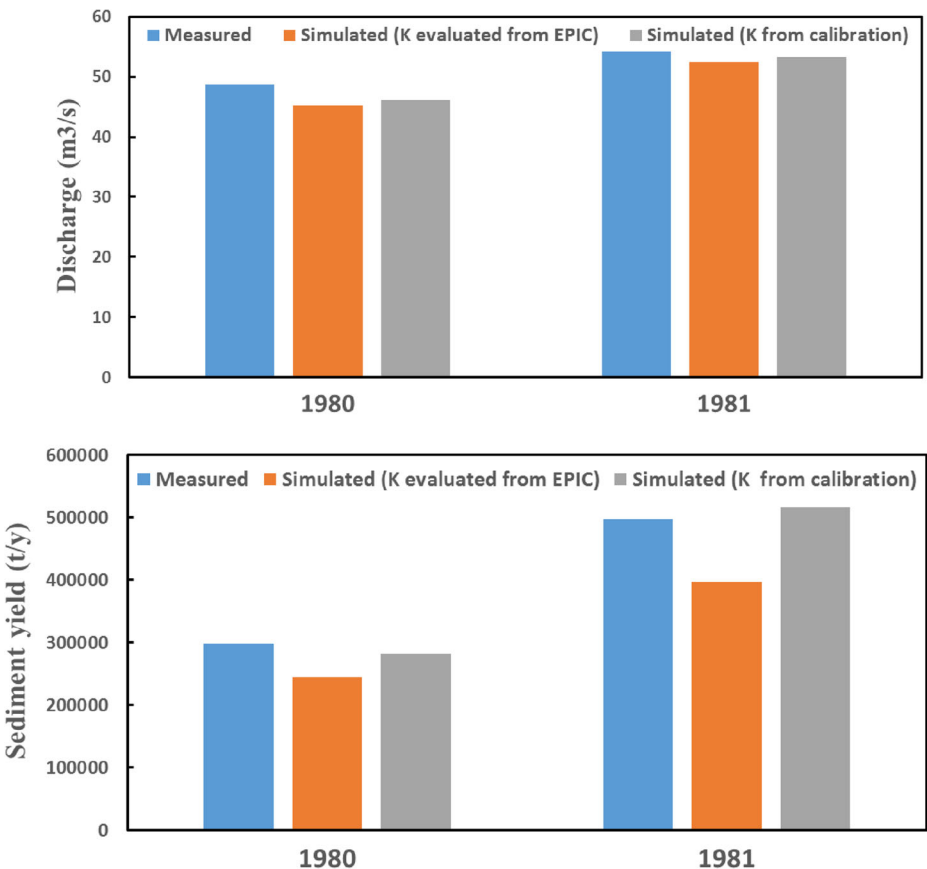


Fig. 11 Measured and simulated values of discharge and sediment yield for years 1980 and 1981

Table 6 Calculated values of annual sediment yield (t/y)

Year	AGNPS	Hrissanthou (2002)	
		Model 1	Model 2
1980	282,355	298,000	278,000
1981	515,476	528,000	588,000
1982	467,195	446,000	426,000
1983	105,124	80,000	73,000
1984	295,626	492,000	494,000
1985	170,985	119,000	131,000
1986	256,752	196,000	198,000
1987	511,482	638,000	673,000
1988	350,203	396,000	383,000
1989	213,839	201,000	207,000
1990	162,335	75,000	64,000

values of sediment yield using the AGNPS model in comparison with the results of two different simulation models by Hrissanthou (2002). The sediment yield in Table 7 is the year average for the whole period of eleven years.

Considerable agreement of the results of the two studies is observed for years 1980–1982 and for years 1988–1989. The greatest proportional discrepancy is observed for years 1984, 1987 and 1990. However, in spite of the differences detected in individual years, the values of mean annual sediment yield for the whole period derived from the present study and the two models by Hrissanthou (2002) are very close.

Another simulation was conducted for the years 2006–2030, after the dam of Platanovrisi was constructed. The inflow of water in the study area is different from that depicted in Figs. 6 and 7, since it is regulated by the dam operation (Boskidis et al. 2011). It was estimated that for the environmental protection of the river downstream of the dams and especially of the river Delta, due to its great ecological significance, a mean daily discharge at least 6 m³/s for the period May to September is necessary. This “ecological” discharge should be available in any case, in spite of increased water demand for other purposes. Taking this into consideration, a constant inflow of 6 m³/s was assumed for the whole period. Although this value is rather arbitrary, since it is not constant for the whole year according to measurements by Boskidis et al. (2011, 2012) for the period 2006–2009, preliminary tests revealed that the inflow has small effect on the results. The rainfall and climatic data for this interval were generated by GLIMCLIM and ClimGen respectively, using existing data for the period 2006–2009. All other parameters were the same as for the simulation for years 1980–1990. The estimated sediment yield for each year is displayed in Fig. 12. The sediment yield fluctuates from 50,000 t/y (year 2025) to 600,000 t/y (year 2016). These fluctuations are analogous to those for the period 1980–1990 (Table 6). The trend line plotted in Fig. 12 shows a tendency for reduction of sediment yield from approximately 300,000 t/y at the beginning of the period to 200,000 t/y

Table 7 Calculated values of mean annual sediment yield for years 1980–1990

Technique	AGNPS	Hrissanthou (2002)	
		Model 1	Model 2
Sediment yield (t/y)	302,852	315,500	319,500

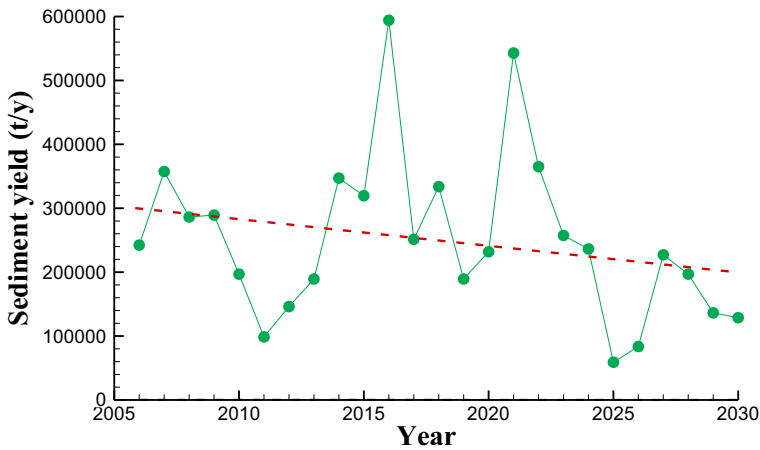


Fig. 12 Estimated sediment yield at location Toxotes for years 2006–2030

at the end of the period. Interestingly, approximately 300,000 t/y is the mean annual sediment yield for the period 1980–1990. Table 8 presents the estimated values of mean annual discharge and sediment yield at location Toxotes for the years 2006–2030. The mean annual discharge is by 5% lower than that for the period 1980–1990, and the mean annual sediment yield lower by 20%. This is in agreement to the study by Liu et al. (2015), according to which, the decrease of runoff from 1989 to 1998 at Beibei Station, in spite of annual fluctuations, is associated with a decrease in the sediment load. The same trend between sediment transport rate and discharge was observed by Metallinos and Hrisanthou (2011) in Nestos River, Greece.

The two simulations suggest that the application of AGNPS yields reliable results. Necessary conditions for the model use are a basin with well-defined boundaries, and the availability of daily rainfall and climatic data, apart from topographic, soil and land use data, including cultivation techniques. In addition, in order to confirm its reliability and make possible adjustments of factors whose evaluation is not absolutely accurate, the model should be calibrated and validated at two different years, not necessarily successive. Therefore, the mean discharge at the basin outlet and the sediment yield of the basin at these two years should be available from measurements.

Since sediment measurements stopped in 1983 and meteorological data, even on a monthly basis, are not available after 2009, the basin is at present unmonitored. Therefore, the present model can serve as a useful tool for the prediction of the annual sediment yield, in spite of the uncertainty, due to the use of rainfall and climatic data generated by GLIMCLIM and ClimGen. Should recorded meteorological data on a daily basis become available in the future, more realistic values of sediment yield may be produced. In such a case, the reliability of the results generated by GLIMCLIM and ClimGen can be assessed.

Table 8 Estimated values of mean annual discharge and sediment yield (Years 2006–2030).

Discharge (m ³ /s)	44.3
Sediment yield (t/y)	252,266

Table 9 Comparison of mean annual sediment yield ratios for Nestos River

References	Gauging station/ Watershed area (km ²)	Mean annual sediment yield ratio [t/(y km ²)]
Gergov (1996)	M. Kula (<i>Bulgaria</i>)/1511	202.0
Gergov and Karagiozova (2002)	Hadgidumovo (<i>Bulgaria</i>)/2123	125.0
Paraskevopoulos and Georgiadis (2001)	Greek-Bulgarian Border/3584	181.0
Paraskevopoulos and Georgiadis (2001)	River Mouth (<i>Greece</i>)/6365	78.0
UNEP/MAP (2003)	River Mouth (<i>Greece</i>)/6100	160.0
Poulos and Alexandrakis (2005)	Temenos (<i>Greece</i>)/4394	157.4
Zarris et al. (2011)	Temenos (<i>Greece</i>)/4954	203.4
Hrissanthou (2002) – Mod. 1	Toxotes (<i>Greece</i>)/838	376.5
Hrissanthou (2002) – Mod. 2	Toxotes (<i>Greece</i>)/838	381.3
This study (1980–1990)	Toxotes (<i>Greece</i>)/884	342.6
This study (2006–2030)	Toxotes (<i>Greece</i>)/884	285.4

Table 9 presents a comparison of mean annual sediment yield ratios for Nestos River with related references (Zarris et al. 2011). The values of mean annual sediment yield ratio are of the same order of magnitude in all studies. Nevertheless, inconsistencies can be detected, which can be attributed to the different data and techniques used, or to different characteristics of the area examined. A large proportional discrepancy can be detected in the values of the two studies at the River Mouth, whereas the difference between the values of the two studies at Temenos is relatively less. In any case, the mean annual sediment yield ratio derived from the present study and by the two models of Hrissanthou (2002) are higher than the values reported in the other studies.

5 Conclusions

The AGNPS software was employed in order to simulate both runoff and sediment transport in the basin of Nestos River, downstream of the hydroelectric dam of Platanovrisi, whose construction was completed in 1997. AGNPS uses factors of the Revised Universal Soil Loss Equation (RUSLE), whose determination is of great importance for the accuracy of results. Topographic, soil and land use data should be available, together with crop-related activities for cropland land uses. A requirement for the use of AGNPS is the availability of rainfall and climatic data on a daily basis. A necessary step before the use of the model as predictive tool, is its calibration and validation. In the calibration process, one or more RUSLE factors are adjusted by a trial-and-error procedure, in a way that the discharge and sediment yield evaluated at the outlet of the basin agree closely with the measured values at a specific year. Then the model should be validated, from the comparison of discharge and sediment yield evaluated from the adjusted factor values, with measurements at a different year. In the present study the erodibility (K) factor, which was evaluated initially for each soil type using the EPIC formula, was used for the calibration and validation. The comparison between calculated and calibrated K factor values suggests that the calculated values, although they can be considered as a satisfactory initial estimate, may not represent accurately the real conditions.

After the calibration and validation, two different simulations were conducted, one for the period 1980–1990 and another for the period 2006–2030, before and after the dam construction. For the former of these simulations (1980–1990), existing meteorological data on a daily

basis were employed. The mean annual sediment yield for the period 1980–1990 was very close to that obtained by a different investigation. Apparently, the good agreement of the mean annual sediment yield acts to reinforce the validity of the present model. The simulation for the period 2006–2030, for which the necessary climatic and rainfall data were generated using the GLIMCLIM and ClimGen software packages, yielded reduced value of the mean discharge by 5% and reduced value of the mean annual sediment yield by 20%, compared to the corresponding values for the period 1980–1990. This constitutes strong evidence that the runoff plays a key role for the sediment yield in a basin, in agreement to other studies.

Availability of Data and Material The data that support the findings of this study are available from the corresponding author on request.

Authors' Contributions All authors, George Paschalidis, Ilias Iordanidis and Petros Anagnostopoulos contributed to the study conception and implementation. The first draft of the manuscript was written by Petros Anagnostopoulos and all authors read and approved the final manuscript.

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Declarations

Conflicts of Interest/Competing Interests The authors declare that they have no conflict of interest.

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